



Research paper

Determining the repair and maintenance cost of wood chippers

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ABSTRACT

Chipping weighs heavily on the total delivered cost of wood fuel, which calls for accurate chipping cost estimates. Chipper repair and maintenance cost is perhaps the most obscure among the figures required for a reliable estimate of chipping cost. To clarify this issue, the authors examined the long-term repair and maintenance records for 51 wood chippers operated by 48 chipping service contractors. Repair and maintenance represented between 1.5% and 29% of total chipping cost, inclusive of fuel and labour (mean = 14%). The ratio between total accumulated repair (TAR) cost and machine price averaged 32% and varied with total use. The relationship between total use and TAR to price ratio was explored through regression analysis, which produced a very strong model ($R^2 = 0.8$). This model predicts a TAR to price ratio of 0.64 at 10000 h, with no significant differences between tractor-driven and independent-engine machines. While the coefficients are different, the structure of this model offers a good match with the repair and maintenance cost models developed for farm tractors and other agricultural machinery. A second model was developed for estimating repair and maintenance cost as a function of fuel consumption. The study also provides reference figures for the contribution of labour cost to total maintenance cost. Farm tractors incur more repairs than preventive maintenance, contrary to the other dedicated components of the chipping operation, where preventive maintenance represents most of maintenance cost. Forestry users should make allowance for the lower structural strength of tractors and select large models.

1. Introduction

A further expansion of the wood energy sector largely depends on the increased availability of biomass fuel at competitive price. This cannot be achieved without improving capacity on the supply side, which is obtained by increasing both the number and the efficiency of chipping operations. To this end, operation managers need reliable data for costing their machines, so that they can offer competitive contract rates and take informed decisions when planning new investments.

Setting a fair contract rate requires an accurate estimate of cost per unit product. This must originate from a good knowledge of the productivity and the operating cost of all equipment used in the operation. Costing is especially difficult in the case of chippers, which have received much less attention compared with other widespread forest machinery, such as feller-bunchers, harvesters and forwarders [1]. Unfortunately, chipping accounts for a large proportion of wood chip cost, and any errors in chipper costing will reflect on the accuracy of production cost estimates.

In fact, several studies offer reliable estimates of chipper productivity [2] and utilization [3], and of such cost items as fuel consumption and depreciation [4,5]. Purchase prices are found on the sale

offers issued from the machine dealers, while resale value can be estimated from the advertisements posted on technical magazines and on the internet. At present, repair and maintenance costs are the least described cost items, which is quite problematic because they constitute a large component in the running cost of agricultural equipment [6]. In fact, chippers operators report larger maintenance needs for chippers compared with the rest of their fleet, which is often based on adapted farming equipment [7]. Furthermore, the repair limit theory postulates that the decision to replace old machinery is normally the consequence of increasing maintenance cost [8], which makes a good estimate the more important.

Maintenance can be corrective or preventive, depending on whether it occurs after or before a failure [9]. Corrective maintenance is also defined as unscheduled, failure-based, event-based, extra-ordinary maintenance, or simply as repair. Preventive maintenance is also defined as scheduled, periodic, time-based or ordinary maintenance. Condition-based maintenance is a more sophisticated form of preventive maintenance, where service is based on careful diagnostics [10].

The need for repair and maintenance derives from routine wear and from accidental damage, both of which are affected by operator care

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[11]. The frequency and severity of failures increase with errors in construction and manufacturing, careless storage of equipment, inadequate preventive maintenance and poor quality of previous repairs - the latter being generally affected by time pressure that derives from the seasonal character of agricultural and forestry work [12].

Maintenance cost is very difficult to estimate for two reasons. First, the frequency and severity of failures is inherently variable, and two apparently identical machines treated in an apparently similar manner may have quite different repair costs [13]. Second, different operators may record different cost figures for the same maintenance intervention, which may depend on different local costs of parts and labor [11], or on different ways to account for the same part and labor costs [14], as when owner time spent on maintenance work is not accounted for [15]. In particular, the records kept by farmers are highly variable for accuracy and completeness, and therefore surveys should include large samples [16].

This study aims to produce reliable figures for the maintenance cost of modern chippers, based on the analysis of documented empirical data obtained from a large sample of machines. More in detail, this research set out to:

1. Explore the relationship between maintenance cost and significant independent variables, such as chipper type, price, age, annual usage, total hours, total production volume and fuel use;
2. Determine the relative contribution to repair and maintenance cost of the main elements of the chipping setup, i.e. the chipping unit, the carrier and the loader;
3. Identify the main cost items, differentiating between repairs and maintenance, and between parts and labor;
4. Producing reference benchmark figures for the elements listed above by relating them to purchase price, resale value, service life, annual usage, production, productivity and fuel use.

The development of significant relationships requires determining other important elements, such as: purchase price, resale value, service life, annual usage, production, productivity and fuel use. Therefore, this study will also pursue the collateral goal of producing reference benchmark figures for the elements listed above.

2. Materials and methods

The study covered a whole range of chipping setups, from light tractor-powered machines designed for part-time use to powerful independent-engine industrial machines best suited to the specialized chipping contractor (e.g. those who carry out chipping as their main full-time occupation). It also included both mechanically-fed and (few) manually-fed units, the latter used by part-time chipping contractors. All machines in the survey were owned and operated by Italian entrepreneurs, and were deployed in Italy, with few exceptions of occasional cross-border activity. Despite its strong Italian character, the study covered a wide range of makes and models - Italian and foreign. Overall, the survey included 51 setups.

For the purpose of the study, machine owners were requested to supply data about: machine price at purchase and current value at the moment of the interview, or at resale if the machine had already been replaced; date of purchase and of the eventual resale; total hours worked from purchase to present, or to resale; total amount (fresh metric tons) of chips produced in the same period; fuel consumption per hour; itemized maintenance cost, subdivided between maintenance and repairs. In that regard, maintenance included all those operations routinely conducted on a regular basis, such as: knife sharpening and replacement; fluids and filters replacement; hose and wear parts replacements; adjustments and periodical checks. In contrast, repairs included sporadic operations that would not occur on a regular yearly basis, such as: engine overhauls and rebuilds; tyre replacements; rebuilding the feeding table or the discharge system; major transmission

work, etc.

All data were to be provided separately for the chipper, the carrier and the loader - if one was used. When the carrier and the loader were not one with the chipper and could be used independently from the chipper for performing other jobs, then the entrepreneurs were asked to indicate the percent of chipping work performed by the carrier and loader, so that their total separate costs could be pro-rated in terms of chipping work only, avoiding redundant attribution (pls. See survey form sample, uploaded as supplementary materials).

In total, 118 operators were contacted. All contractors performed chipping as a full-time specialized occupation, or as a part-time job complementary to a main occupation in the logging sector. All operators were contacted by phone before sending the survey form. Understandably, not all entrepreneurs had kept records of the required quality, or were willing to search their files in order to track all relevant maintenance records for the whole life of their machines. For this reason, the study is based on 51 machines only, which represent 48 respondents who could guarantee sufficient data quality. Once the survey form was received, follow-up phone calls were used to clarify any doubts and/or integrating missing data. The work was started in late 2016, and lasted almost 18 months until February 2018.

All surveys were consolidated into a single data file for statistical analysis, which was conducted using SAS Statview 5.1 [17]. Before analysis, all price and cost figures were revaluated to 2017 currency equivalents, using the dedicated calculator provided by the Italian Statistical Agency [18]. Then, descriptive statistics were calculated, separately for the main machine classes. The statistical significance of any differences between machine classes were tested with parametric and non-parametric tests, depending on the characteristics of the data. After that, the complete database was analyzed with regression techniques, in order to establish the significance of any relationships between maintenance cost and such independent variables as: chipper type, price, age, annual usage, total hours, total production volume and fuel use. The elected significance level for all analyses was $\alpha < 0.05$.

3. Results

3.1. Machine characteristics

The 51 operations surveyed represented a wide range of machines (please see [Appendix A](#)), from very small (51 kW) to very large (456 kW). Due to this large size variation, the capital investment tied in a single operation ranged from less than 24000 € to over 850000 €, inclusive of loader and prime mover ([Table 1](#)). Twenty-one machines (39%) were fitted with their own independent engines, whereas 30 were driven by the engine of their carriers, using a power-take off (PTO). Except for two machines, PTO-driven chippers were joined to farm tractors.

Drum chippers constituted the majority of the chippers in this study: only 7 machines (14%) were disc chippers and they were all small PTO-driven models, powered by engines below 150 kW (mean power of disc chippers = 82 kW). The two smallest machines - both PTO-driven models - were fed by hand, while the rest used a hydraulic knuckle-boom loader.

Italian, German and Austrian makes accounted for the largest share of the sample (45% and 41%, respectively), which was dominated by *Pezzolato* and *Jenz* with 20 and 11 machines, respectively. Nordic and Northamerican makes represented the remaining 14%. That corresponded to anecdotal evidence about the Italian chipper fleet, and may reflect the wider Central European market.

The data spanned over a wide range of machine ages, use and use intensity, and namely: from 1 to 24 years; from 200 to 19000 h; from 30 to 2000 h year⁻¹. Eight machines had been bought used, after clocking between 2500 and 6500 h (mean = 4172 h). The price and maintenance cost figures for these machines were those provided by their current owners (those who were responsible for supplying the data) and

Table 1
General outlook of study results (51 observations).

		Mean	SD	Minimum	Maximum
Power	kW	211	124	51	456
Price	€	228900	183400	23600	851200
Price*	€ kW ⁻¹	1018	393	357	1980
Retention	%	47.5	15.7	12	88
Use	Years	6.6	4.1	1.3	24.3
Use	h	3526	3862	210	19500
Use	t	51300	80300	1050	487500
Use intensity*	h year ⁻¹	577	491	30	2040
Production*	t year ⁻¹	8680	10180	150	37650
Productivity*	t h ⁻¹	11.9	9.0	1.2	38.9
Fuel use*	l t ⁻¹	2.9	1.9	1.4	13.7
Chipping cost*	€ t ⁻¹	21.3	18.4	5.6	73.9
R&M cost*	€ t ⁻¹	2.2	1.3	0.4	7.5
R&M cost*	% total	14.1	7.1	1.5	28.6
R&M cost*	€ h ⁻¹	20.2	12.0	2.8	50.6
R&M cost*	€ year ⁻¹	13720	14410	160	66100
R&M cost*	TAR/Price	0.32	0.24	0.01	1.01
R&M cost*	% depreciation	60	40	2	156

Notes: SD = standard deviation; All price and cost figures were revaluated to 2017 values; t = fresh metric tons (1000 kg); TAR = total accumulated repairs, i.e. the total cost of repairs at the time of observation, revaluated for the date when the observation was made; * Derived figure calculated by the Authors based on the original figures actually provided by the respondents (e.g. *Productivity* in t h⁻¹ was derived from the original figures provided by the respondents for *Use* in t and *Use* in h - by dividing t by h, individually for each machine).

accounted for the purchase price of the used machines and for the maintenance cost after that date.

There were significant differences between independent-engine and PTO-driven units, which may have reflected on maintenance cost. First of all, the average independent-engine operation was twice as powerful and expensive to buy as the average PTO-driven operation. However, the investment per kW was approximately the same, when this figure was referred to the whole operation inclusive of carrier and loader (Table 2). Second, independent-engine chippers were coupled to a farm tractor in 4 cases only (20%), while PTO-driven chippers were almost always coupled to a farm tractor (29 machines out of 31, or 94%). Third, while 60% of the independent engine chippers were fitted with an integral loader, only 30% of the PTO-driven units were. Based on this information, a reasonable conclusion is that independent-engine

chippers were most often the core of large specialized operations, while PTO-driven chippers represented smaller part-time operations. Such approximation found support in the higher productivity achieved by the independent-engine units, compared with PTO-driven units. However, several PTO-driven machines did integrate high-output, specialized operations and could effectively compete with independent-engine units for power and productivity. Although approximate, this generalization was made because a clear understanding of differences between chipper types may be useful for interpreting the results of the maintenance study and defining their external validity.

3.2. Maintenance cost by component and operation type

Survey data indicated that repair and maintenance may represent between 1.5% and 29% of total chipping cost, inclusive of fuel and labour: mean incidence was 14%, and corresponded to 2.2 € t⁻¹ of chips (Table 2). Depending on machine type and use intensity, chipping operators may expect to spend between 200 € and 60000 € per year on machine maintenance. The mean value was 13700 € year⁻¹ and the median 7500 € year⁻¹, pointing at a clear skew in data distribution towards machines that were smaller and/or less intensively used than the average.

Maintenance cost is generally related to machine size and price, and for this reason it is best expressed as the ratio between total accumulated repair (TAR) cost and machine price. In this study, TAR represented the cumulative cost of all maintenance performed until the date of the survey or that of resale - if resale occurred earlier. This figure averaged 32% and ranged between 1% and 100%). Once expressed as a percent of depreciation, maintenance cost averaged 59% of depreciation for a machine with 3500 h, and 121% for a machine with 10000 h.

All these figures accounted for the whole chipping operation, comprised of chipper, loader and carrier. Among them, the chipping unit accounted for the largest share of maintenance cost, regardless of operation type (Fig. 1). In contrast, carrier maintenance was larger for PTO-driven units compared with independent-engine units, and that was consistent with the more important role played by the carrier within PTO-driven operations, where the carrier supplied both power and locomotion and not just the latter. More in general, PTO-driven units incurred half the annual and hourly maintenance cost of independent engine units: however, their maintenance cost per unit

Table 2
Main study results by machine type.

		Independent (n = 20)		PTO-driven (n = 31)		P-Value
		Mean	SD	Mean	SD	
Power	kW	321	91	141	85	< 0.0001
Price	€	333180	197000	161600	139800	0.0004
Price	€ kW ⁻¹	990	390	1040	400	0.6996
Retention	%	47.1	17.0	47.8	15.1	0.7723
Use	years	6.1	3.7	6.8	4.4	0.5053
Use	h	4343	4820	2999	3068	0.3155
Use	t	84800	109500	29700	43900	0.0025
Use intensity	h year ⁻¹	697	474	500	493	0.0712
Production	t year ⁻¹	14700	12100	4800	6300	0.0007
Productivity	t h ⁻¹	19.1	9.1	7.3	5.1	< 0.0001
Fuel use	l t ⁻¹	2.2	0.7	3.3	2.2	0.0151
Cost	€ t ⁻¹	13.5	14.8	26.5	18.9	0.0008
R&M	€ t ⁻¹	1.7	0.9	2.5	1.4	0.0206
R&M	% total	16.6	6.8	12.5	6.8	0.0390
R&M	€ h ⁻¹	28.9	11.4	14.6	8.7	< 0.0001
R&M	€ year ⁻¹	20420	15140	9390	12320	0.0036
R&M	TAR/Price ⁻¹	0.373	0.285	0.285	0.199	0.2975
R&M cost	% depreciation	68	44	54	34	0.2836

Notes: SD = standard deviation; All price and cost figures were revaluated to 2017 values; t = fresh metric tons (1000 kg); TAR = total accumulated repairs, i.e. the total cost of repairs at the time of observation, revaluated for the date when the observation was made.

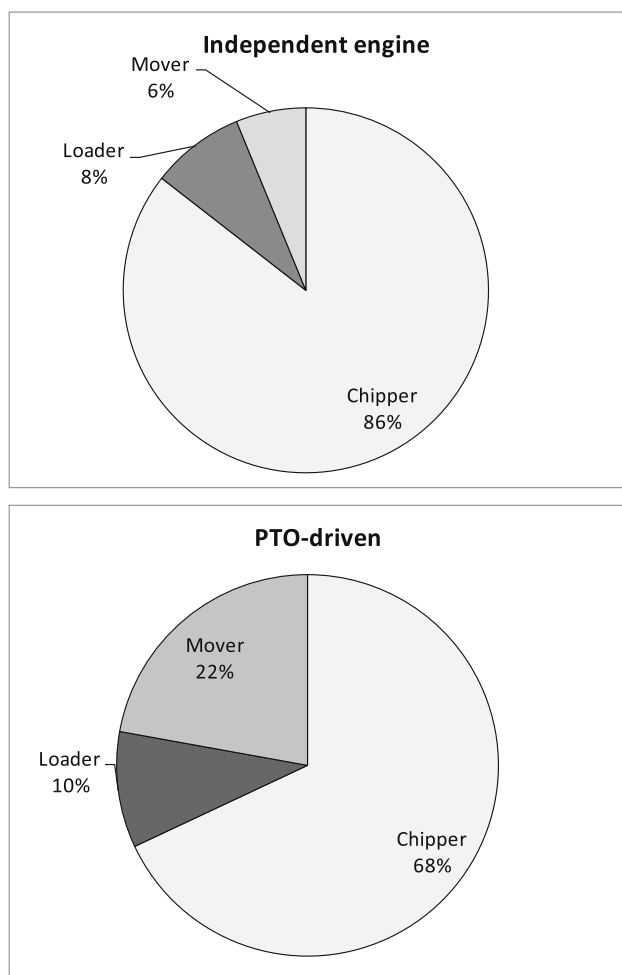


Fig. 1. Breakdown of maintenance cost by operation component.

product was 50% higher, due to their lower productivity. On the other hand, there were no significant differences between the two operation types concerning the TAR to price ratio, leading to the conclusion that most of the other differences were due to scale effects, determined by the larger size of independent-engine chipper operations.

As a general average, preventive maintenance accounted for 74% of total repair and maintenance cost, but there were differences between machine types and operation components. With independent-engine chipper operations, repairs represented approximately 30% of the repair and maintenance cost for each of the three components: chipper, loader and carrier. Conversely, with PTO-driven chipper operations, repairs accounted for only 17% of the chipper repair and maintenance cost, and for over 40% of that for the carrier, suggesting a high strain and/or an inherent structural weakness of tractor-based carriers. Interestingly enough, 7 out of 28 (25%) tractor-powered operations replaced the original carriers with 50% larger ones after the first few years of service as the original machines were deemed too weak and required excessive maintenance.

Such claims were tested by analysing the causes for repairs on tractors used to drive chippers. Two-thirds of the interventions were equally split between the engine and the transmission, but engine repairs were much more expensive and accounted for 50% of the total cost of tractor repairs. Transmission repairs represented 20% of the repair cost incurred by tractors. Tyre replacements were the third most frequent corrective maintenance intervention recorded for farm tractors, accounting for 15% of the events and 12% of the cost. As a further step, these figures were compared with the same engine, transmission and tyre repair figures recorded for independent engine operations

(Table 3). The analysis only considered the clutch, gearbox, reduction and shaft elements in the transmission and not the belts, because the latter are part of the chipper - not the tractor - and the analysis aimed at detecting tractor reliability issues. Statistical analysis confirmed a significant difference in the distribution of repair events, with tractors incurring twice as many engine and tyre repair events, compared with independent engine operations (χ^2 : p-value = 0.020). There was a high variability in cost for single repair events and thus no statistically significant differences were found between the two setups. The data suggest that tractors have much larger engine and tyre repair cost than independent-engine chippers, both in terms of cost per single event and cost over machine life. The contrary was true for transmission repairs, but as transmission repairs were uncommon, only three of the independent-engine operations actually incurred any transmission repairs, this result should be considered with much caution.

Concerning the chipping unit, 20% of the maintenance cost was evenly distributed between the feeding and the expulsion systems, while 80% was related to knife management and included knife sharpening, as well as knife, knife holder and counter-knife replacement (Fig. 2). The duration of a knife set before sharpening ranged from 14 to 240 t. Sharpening was more frequent for low-production operators, and some of them affirmed they would routinely sharpen the knives at the end of the working day, regardless of actual wear (Fig. 3). If very low-output operations ($\leq 2000 \text{ t year}^{-1}$) were removed from the analysis, then the average amount of chips produced between two sharpening sessions commonly varied from 100 to 180 t. In that case, there was no significant difference between disposable and conventional reusable knives. In fact, some of the best performance figures were obtained with disposable knives.

3.3. Modelling maintenance cost

Statistical analysis yielded several models describing a significant association between maintenance cost and some of the main operation characteristics, such as machine power and price, age, total production in tons and total service in hours. However, the effect of some independent variables was modest, and the increased explanatory power obtained by including these variables did not justify the additional complication derived from trying to obtain a reliable estimate for their values. Obtaining a reliable estimate from a model requires that all independent variables are measured with accuracy, which takes time and effort. If the inclusion of an additional variable increases the regression coefficient from 0.828 to 0.835, one should consider quite carefully about settling for the simpler original model that is basically as good, but is easier to use and does not incur the additional error risk. The models reported in this paper offer the best compromise between high explanatory power and user-friendliness, and exemplify two alternative approaches (Table 4). The first model has the classic structure already described in many tractor maintenance equations and is designed to estimate the ratio between TAR and revaluated machine price as a function of wear, expressed as total hours worked at the date of the estimate. An indicator variable was introduced for achieving better accuracy when dealing with machines that were bought used. With these machines, reliable information about TAR to the date of the second purchase is generally unavailable, and one must do with the partial record maintained after that date. However, excluding these machines from the model would offer a poor service to buyers of second-hand equipment. This model is highly significant and explains over 80% of the variability in the dataset. When used on second-hand machines, the model assumes a mean accumulated use of approximately 4000 h at the time of the second buy. The model predicts a TAR to price ratio of 0.64 at 10000 h (e.g. $0.0003048 \times 10000^{0.83} = 0.64$), with no significant differences between PTO-driven and independent-engine machines (Fig. 4).

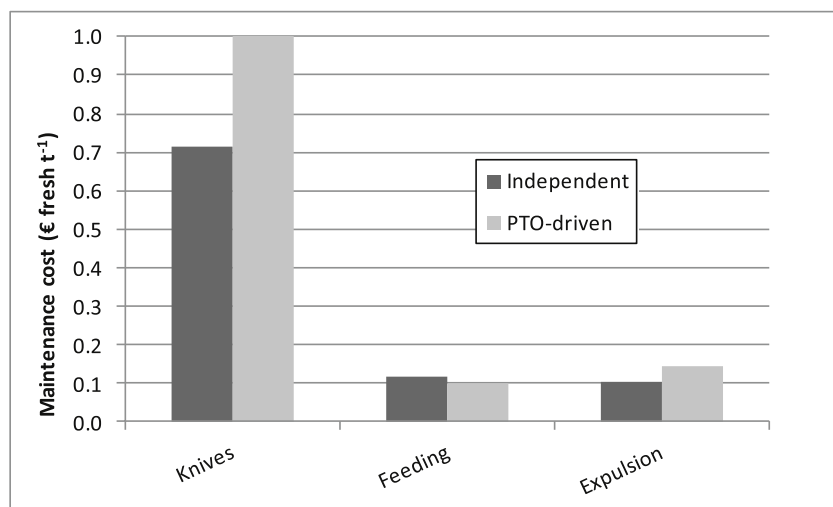
The second model relates maintenance cost in € t^{-1} to fuel consumption in l t^{-1} . The model is based on the assumption that fuel use is

Table 3

Corrective maintenance for engine, transmission and tyres.

System	Events machine ⁻¹		€ machine ⁻¹		€ event ⁻¹	
	PTO-driven	Independent	PTO-driven	Independent	PTO-driven	Independent
Engine	0.4	0.2	2973	1409	7680	7044
Transmission	0.5	0.4	1088	3319	2410	8297
Tyres	0.2	0.1	697	188	3602	1876

Notes: Events machine⁻¹ and € machine⁻¹ represent mean figures, recalculated for the whole fleet. On PTO-driven machines, engine, transmission and tyres are those on the tractor. Transmission repairs include clutch, gearbox and reductions, but exclude belts.

**Fig. 2.** Chipper maintenance cost by machine system.

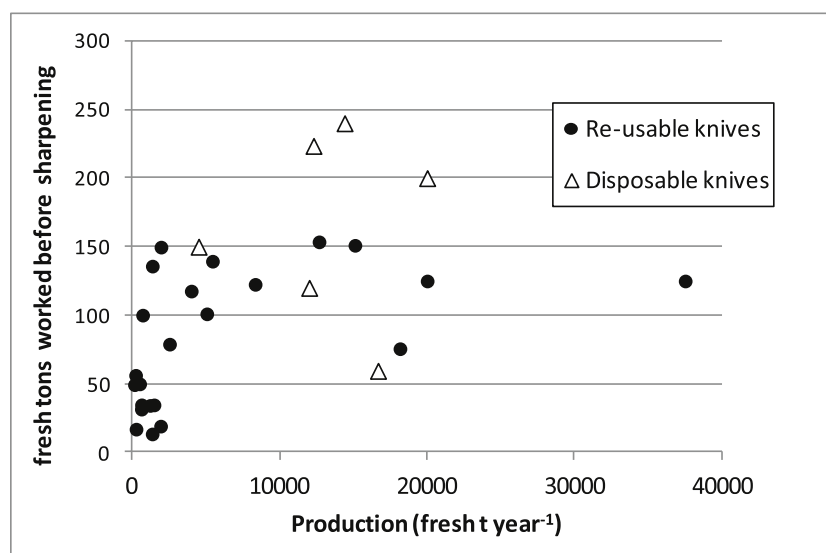
an indicator capable of integrating the effects of machine size, wear and work conditions. While fuel cost per ton rather than fuel use per ton would be a more consistent indicator, a non-monetary independent variable is used, in order to dim the confounding effect of variable fuel price across Europe. This model can still explain two thirds of the variability in the data and it is very convenient to use: it simply says that maintenance cost in € per ton is 0.57 times fuel use in litre per ton. In short, if fuel consumption is measured at 31 t⁻¹, then repair and

maintenance cost can be estimated at 1.7 € t⁻¹ (e.g.: 3 * 0.57 = 1.7).

4. Discussion and conclusions

4.1. Study limitations

First of all, it is important to state the limitations of the study and frame the validity of any statements made in the following discussion.



Notes: Re-usable knives = standard re-usable knives, re-sharpened 10 to 20 times before discarding; Disposable knives = single-use knives, thrown away when dull.

Fig. 3. Fresh metric tons worked by a knife set before sharpening, by knife type and annual production.

Table 4
Models for predicting maintenance cost.

TAR/price = a * Hours ^{0.83} + b * Hours * Used				
R ² adjusted = 0.828; n = 51; F = 123.4; p < 0.0001				
Coefficient		SE	t-Value	P-Value
a	3.048*10 ⁻⁴	2.148*10 ⁻⁴	14.194	< 0.0001
b	8.635*10 ⁻⁵	2.500*10 ⁻⁵	3.454	0.0011
R&M = a * Diesel				
R ² adjusted = 0.671; n = 48; F = 99.0; p < 0.0001				
Coefficient		SE	t-Value	P-Value
a	0.574	0.058	9.948	< 0.0001

Notes: Hours = total hours worked at the time of the estimate; Used = indicator variable: 0 if the chipper was bought new, 1 if the chipper was bought second-hand; n = number of observations; SE = standard error; R&M = repair and maintenance cost in € t⁻¹; Diesel = diesel fuel consumption in l t⁻¹.

The main limitations are: the national character of the sample, the reliance on company records and the inherent variability of machine maintenance data.

One may wonder about the capacity of a purely Italian sample to represent the situation in other countries. While operations and technology used are relatively homogeneous across much of central Europe, the cost of labor, fuel and parts can differ widely between countries. This is likely to impact the maintenance cost estimates. That is one of the reasons why the analysis focused on dimensionless ratios, which are somewhat resilient to the effect of local cost variations. Therefore, caution is needed when applying results outside of Italy. However such a generalization is likely better than an informed guess, until specific regional data become available.

The use of company records causes some limitations, because these data are not collected according to any standardized method and may present variable accuracy. In particular, the company records may be flawed by omission, approximation and transcription errors derived from rushed or incomplete compilation. Furthermore, these records may present misallocation of items, or lumping of more different items into a single figure. Even when a whole list of bills was attached to the survey form, there was no way to know if any bills had been omitted or lost. Furthermore, some bills were “lumped bills”, where a single figure either accounted for the cost of different interventions or included

labour cost with the cost of spare parts. These limitations were counteracted by aggregating several items into larger fundamental categories, which were more likely to be recorded in a common way, making the dataset somewhat robust against inaccurate recording practice.

Moreover, contractors who did not have good records or felt uneasy about allowing access to their data could simply decide not to supply any records, and there was little reason for anyone to provide inaccurate or unreliable values. The general consistency of the dataset indicate that this effort was rewarded, and that contractor responses were accurate enough for the purpose of the study. Flagrant inaccuracy would have been exposed by large variations in the material and recurring outliers neither of which materialized.

Finally, the dataset was certainly affected by the inherent variability of repair and maintenance data already reported by e.g. Abdelmoteleb [11]; Bowers and Hunt [19]; and [20]. This is an effect of a number of factors that are very difficult to capture, such as: machine characteristics, conditions of use, operator care and skill, local dealer cost. In addition, repair and maintenance needs are strongly affected by random variation [13] and that is the reason why this study was based on the largest possible sample, which must have integrated the effect of random variability, at least to some extent.

This said, the present study is so far the only one offering long-term maintenance data from a number of chipping contractors. Furthermore, the dataset spans a wide range of conditions with a reasonably even distribution, which makes it quite solid and facilitates detection of the main trends, in the least. To our knowledge, no other similar studies about chipper maintenance are based on such a large and varied dataset.

4.2. Comparison with other studies

The unique character of the study makes it difficult to find direct comparisons. The only other study specifically addressing chipper maintenance is based on data from 7 industrial machines in Estonia [21]. It reports similar figures for maintenance cost, which is estimated between 9 and 23% of total cost [21].

On the other hand, the empirical figures obtained from this study can be compared with the theoretical figures reported in other studies about chipper cost. Most such studies present chipper maintenance cost as a percent of chipper depreciation, and estimate it at 75% [22], 80% [23], 100% [24] or 110% [25] - all of which fall below the 120% value reported here. On the other hand, those studies that present maintenance cost as a percent of total chipping cost generally exceed the

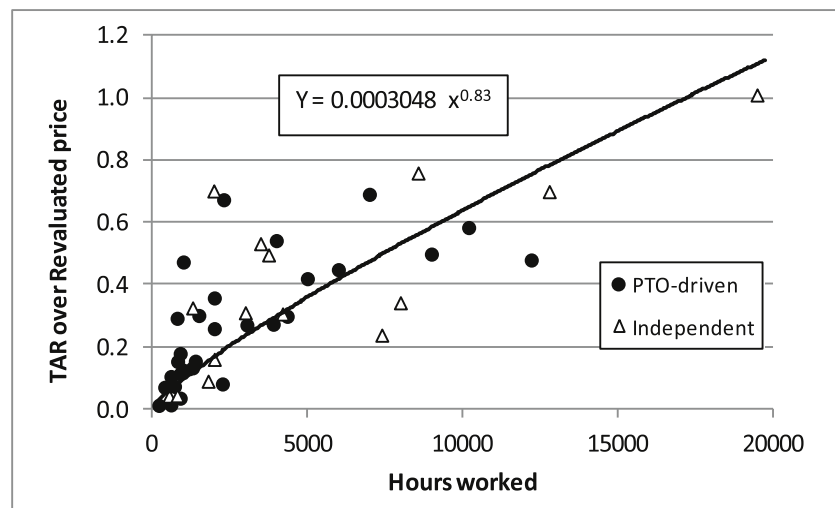


Fig. 4. Total accumulated repair (TAR) over revaluated price as a function of total use in hours (graph for new machines only).

mean 14% figure found in this study and point at 18% [26] or 20% [27]. The same occurs when maintenance cost is reported as a TAR to price ratio, because literature estimates amount to 0.8 [28] or 0.9 [25], not 0.6. It is important to notice that all the studies reporting higher maintenance cost figures come from north America and the eventual discrepancies may simply point at a regional difference, due to variations in the balance between individual cost factors.

Repair and maintenance cost figures reported for other forest machine types vary from 5 € h⁻¹ [29] to 28 € h⁻¹ [30] and span such a wide range that they are bound to include the cost figures reported in our study without offering a very strong corroboration: comparison with other forest machine studies can only hint at the general expected size of maintenance cost and confirm the absence of gross errors, but nothing more.

4.3. Maintenance cost models

The models produced in this study offer a good match with the maintenance cost models listed in the subject literature. This presents many different model types, and the first equation in this study adopts the same dependent variable and the same power form reported in the fundamental work published by ASABE [31] and by Ward et al. [32]; for farm tractors and other agricultural machinery. This form was chosen for predicting chipper maintenance cost not only for the excellent fit to the experimental data, but also because comparative studies reported it to be best among the various alternatives [33]. Similarly, use of total accumulated repair cost as a dependent variable is known to result in a higher predictive power than achieved when using other variables to represent maintenance cost [34]. The main difference between the equation presented in this study and those published by ASABE or Ward et al. is that here the independent variable is the absolute number of hours in service, and not their ratio to the maximum expected service life - i.e. the proportion of service life already spent at the time data was collected. Using an absolute figure dispenses with estimating service life, which may vary due to working conditions, contractor policies and machine performance. Current literature only offers rough estimates of chipper life, more an acknowledgement that this can exceed 6000 h rather than a real reference figure [5], as necessary for a classic equation in the ASABE style. In fact, using an absolute figure for chipper use is likely better than trying to estimate an use-to-service life ratio when modelling maintenance cost, due to the uncertainties in service life estimations. Moreover, the equation presented in this study is also an improvement over earlier methods used for estimating the maintenance cost of forest machinery [24,35,36], because all these methods estimates average annual maintenance cost based on a fixed depreciation period. The model reported in this study can produce a reliable estimate of maintenance cost at any moment along the service life and can be used for assessing the right time for machine replacement.

It is worth noting that the first model presented in this paper uses an exponent smaller than 1, whereas the exponent on most other models is larger than 1. That produces a convex curve instead of a concave one and indicates that the ratio of TAR to price grows with use, but at slightly decreasing rates. While partly the result of formulating the independent variable as a ratio, this shape may have an impact on replacement decisions, because it shows that postponing replacement after extended use does not necessarily result in maintenance cost getting out of control. Instead, maintenance cost seems to slowly creep upwards with further use.

Of course, sole reliance on maintenance cost increases can be deceitful, because replacement decisions must also be based on information about the production losses derived from declining mechanical availability [37] and efficiency losses compared to newer machines. Future research should address the relationship between machine wear and mechanical delays, offering contractors a complete toolbox for machine replacement decisions.

Only one other paper tries to associate maintenance cost with fuel use [14], but the idea is interesting. Fuel use is affected by the same factors that affect maintenance cost, and in the same direction. Fuel use increases with machine size, with hours of use (as a consequence of wear) and with years of use (as a consequence of obsolescence). Careless or inexperienced drivers will also incur an increase of fuel use and maintenance cost. Therefore, it seemed logical to look for a function that linked fuel use and maintenance cost. The model proved highly significant and confirmed the possibility of using fuel consumption as a simple coefficient for a quick estimate of chipper maintenance cost.

4.4. Cost components

An additional merit of this study is to provide estimates that explicitly include labour cost, which is excluded in some of the other maintenance studies [15]. In fact, uncertainty about the inclusion of labour cost and labour rate variability are considered as important confounding factors in maintenance cost research [6]. This study provides reference figures for the contribution of labour cost to total maintenance cost, which can be used to correct those estimates that do not include labour cost.

The study also confirms previous information about knife wear [38] and highlights the importance of fine-tuning knife management, since that accounts for the largest share of chipper maintenance cost. While one may easily calculate the point of minimum cost, where the savings accrued from extended knife service match the costs derived from decreased productivity and increased fuel consumption, such calculation requires accurate knowledge of knife conditions, which is difficult due to the random effect of feedstock contamination. Future research may address the development of simple diagnostic tools for assisting operators with knife sharpening decisions, according to the principles of condition-based maintenance. It is worth noticing the premature knife sharpening routine applied to several small machines. That is a questionable practice that may find justification in the desire not to stop for knife sharpening during the working day. On the other hand, apparently premature knife sharpening may indicate the use of an underpowered tractor, which can offer acceptable performance levels only when the knives are in top conditions. One cannot help noticing that one-third of the PTO-driven operations under 100 kW are subject to premature sharpening, and that one-third of those above 100 kW have replaced their previous tractor with a much larger one. That seems to point at a poor understanding of the significant power demand required by a chipper. Frequent use of underpowered tractors may find corroboration in the fact that engine repairs are more frequent and expensive for PTO-driven operations compared with independent-engine operations. In contrast, the higher tyre repair cost of PTO-driven operations may simply hint at a different use pattern, whereby tractor-powered units are used more often than independent-engine units for terrain chipping - i.e. chipping at the stump site, instead than at the roadside. That would increase the chances of tyre punctures or busting.

While farm tractors are reliable and sophisticated machines, they are not designed for forestry work and may lack the structural strength required for such job [39]. At least, that is what one may infer from the results of this study, which shows how farm tractors incur much more repairs than preventive maintenance, contrary to the other dedicated components of the chipping operation, where preventive maintenance represents the bulk of maintenance cost. Generally, farm tractors seem to be subject to a relatively high incidence of repairs [40], but forestry users should make special allowance for the lower structural strength of these machines and select large models, even when they seem oversized.

PTO-driven operations offer the same good performance as independent-engine operations both in terms of productivity [5] and maintenance cost (here), and the preference for one or the other solution is likely dependent on the mobility and flexibility needs of each individual contractor. Independent-engine units are normally best in

case of frequent long-distance relocation, while PTO-driven operations are preferable when flexible use is required [4].

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Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biombioe.2019.01.024>.

Appendix A. List of machines in the survey

Make	Model	Carrier	Type	kW	Year
Conehead	V3000	None	Independent	110	2010
Doppstadt	DH 810	Truck	Independent	456	2013
Erjo	12/90	Forwarder	Independent	430	2003
Eschlboeck	Biber 7	Tractor	PTO	82	2010
Eschlboeck	Biber 80	Tractor	Independent	314	2003
Farmi	260 CH	Tractor	PTO	75	2003
Farmi	260 CH	Tractor	PTO	77	2006
Farmi	260 CH	Tractor	PTO	81	2006
Gandini	CT 30-60	Tractor	PTO	74	2013
Gandini	TPS 35	Tractor	PTO	107	2013
Gandini	TPS 35	Tractor	PTO	125	1993
Heizohack	8–400	Tractor	PTO	59	2005
Heizohack	6–400	Tractor	PTO	96	2012
Heizohack	14–800	Truck	Independent	280	2013
Jenz	HEM360 Z	Tractor	PTO	132	2010
Jenz	HEM 561 Z	Tractor	PTO	199	2014
Jenz	HEM 560D	None	Independent	335	2004
Jenz	HEM561 D	Truck	Independent	335	2006
Jenz	HEM 561D	Tractor	Independent	335	2007
Jenz	HEM 561 DQ	Truck	Independent	335	2014
Jenz	HEM 582R	Truck	PTO	353	2010
Jenz	HEM 561 D	Truck	Independent	360	2012
Jenz	561 HEM	None	Independent	361	2013
Jenz	HEM 820 DQ	Truck	Independent	456	2014
Jenz	HEM 820 DL	Truck	Independent	456	2014
Morbark	Hurricane XL2400	None	Independent	177	2007
Muss-max	Terminator 8	Tractor	PTO	133	2008
Muss-max	Terminator 7	Tractor	PTO	169	2005
Muss-max	Terminator 8	None	Independent	224	2007
Pezzolato	H 780	Tractor	PTO	52	2007
Pezzolato	PTH 300	Tractor	PTO	59	2012
Pezzolato	H 780/200	Tractor	PTO	63	2008
Pezzolato	PTH300	Tractor	PTO	81	2013
Pezzolato	PTH 400	Tractor	PTO	96	2011
Pezzolato	PTH 400	Tractor	PTO	96	2012
Pezzolato	PTH 300	Tractor	PTO	99	2014
Pezzolato	PTH 770/660 G	Tractor	PTO	110	2009
Pezzolato	PTH 400	Tractor	PTO	118	2013
Pezzolato	PTH 400 XL	Tractor	PTO	118	2013
Pezzolato	PTH 480/660 M	Tractor	PTO	132	2005
Pezzolato	PTH 900/660	Tractor	PTO	185	2010
Pezzolato	PTH 900/660 L	Tractor	PTO	224	2011
Pezzolato	PTH 900/660 M	None	Independent	236	2010
Pezzolato	PTH 900/660 L	Tractor	PTO	261	2009
Pezzolato	PTH 900/660 M	Tractor	Independent	262	2013
Pezzolato	PTH 900/660	Tractor	PTO	280	2009
Pezzolato	PTH 900/1000 M	Tractor	Independent	309	2002
Pezzolato	PTH 1000/1000 M	Truck	Independent	316	2014
Pezzolato	PTH 1000/820	Truck	PTO	353	2015
Vermeer	HG4000	None	Independent	328	2014
Wust	KPC12	Tractor	PTO	276	2014

Notes: kW = Engine power; Year = Year of manufacture; PTO = Power take-off. It denotes a machine without its own power pack, and powered by another vehicle: truck or tractor; If "Carrier" = "None", then the chipper is mounted on a trailer and does not have a dedicated tractor for moving it around, but it is relocated using movers of opportunity.

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